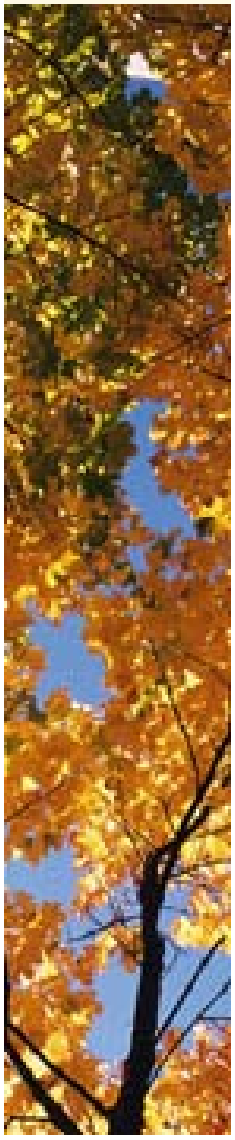

Tracer Testing Techniques to Support Design and Operation of In Situ Remediation Systems

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Applied Tracers

Definition:

Unique constituent intentionally introduced to aquifer

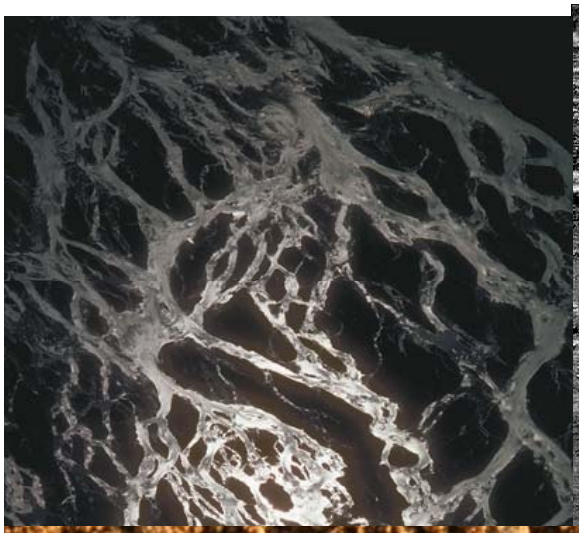
Why Powerful:

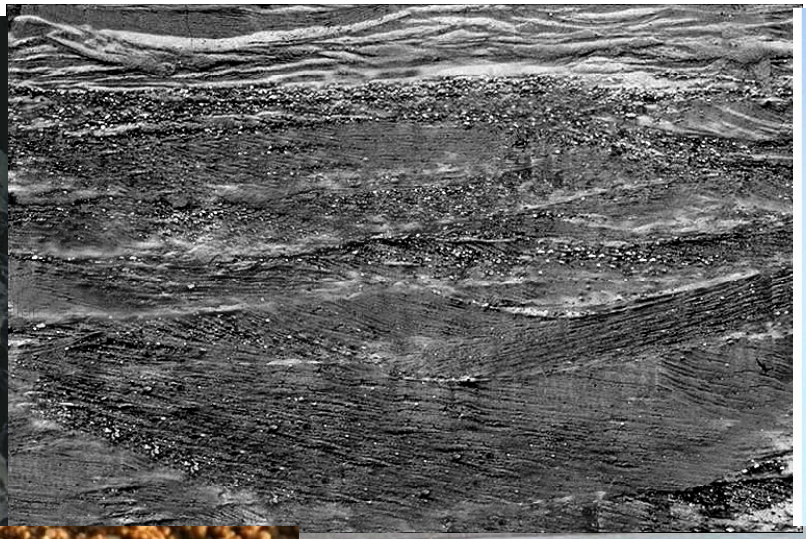
Source term is controlled and well characterized

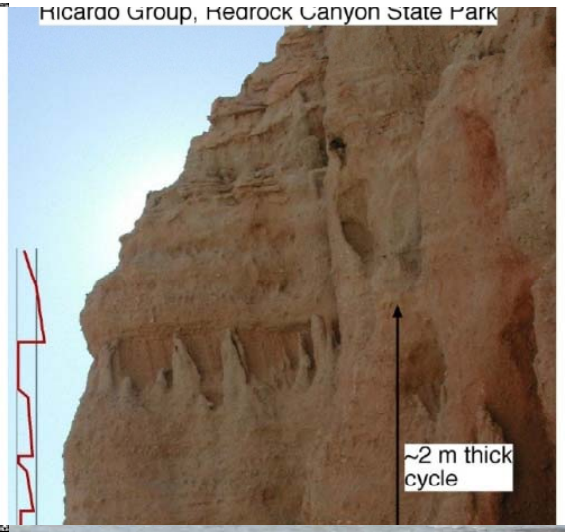
- ~10 AD: Flavius Josephus: chaff tracer identifies source of Jordan R.
- Late 1800s: Quantitative tracer tests using fluorescent dyes, salt, and bacteria in karst aquifers
- 1945-1955: Advances in chemical measurement increased power and made high-frequency sampling economically feasible
- 1965-1970: 650 papers

  1995-2000: 6500+ papers
- Now routinely used in "non-research" applications
  - ARCADIS uses tracers to support design of all in situ systems

Aquifers are Heterogeneous and Anisotropic as a Rule!





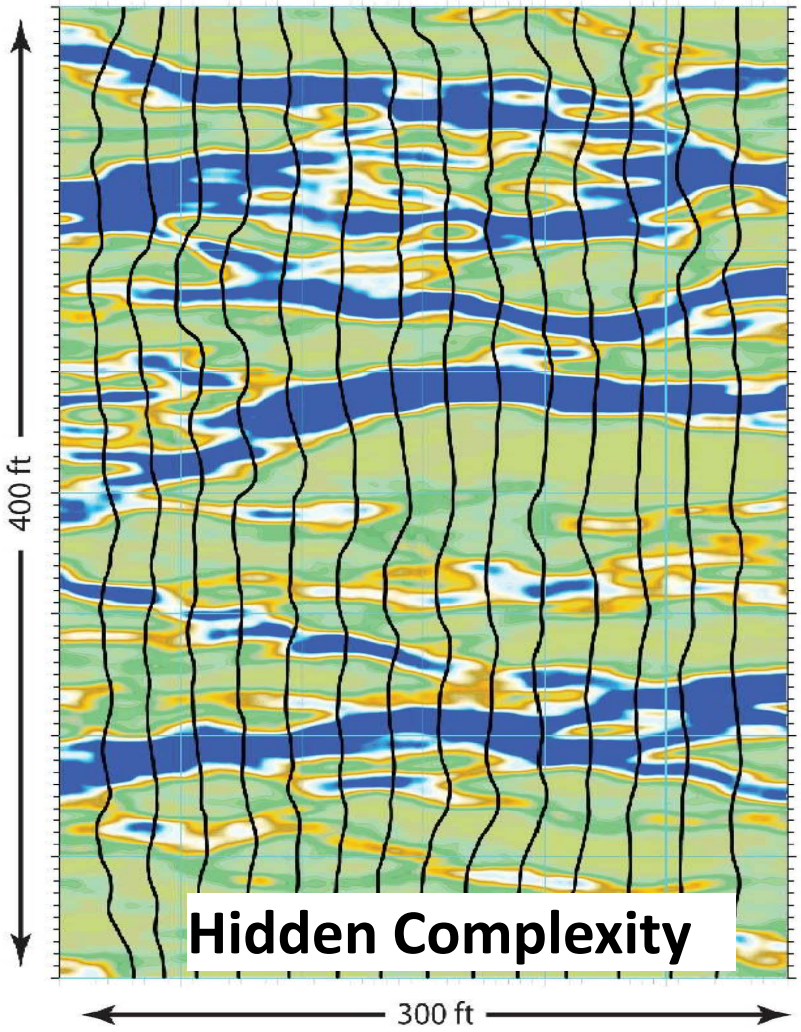


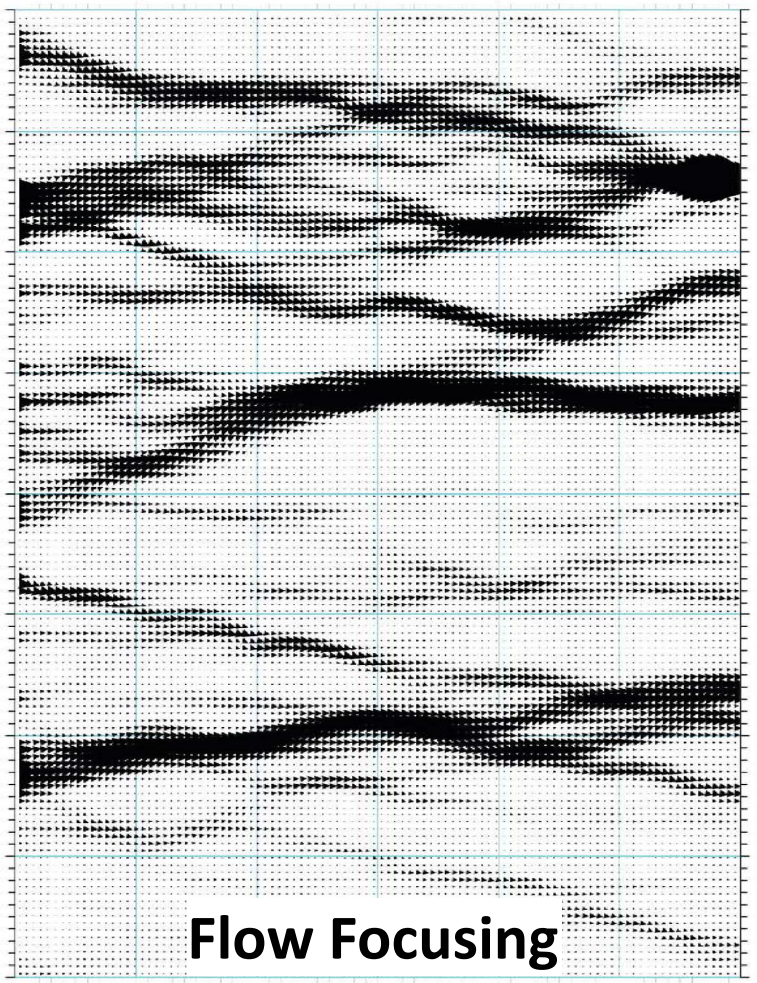
Geology controls distribution and transport of injected fluids and solutes

- The success of in situ remediation systems requires site specific understanding and tailored design
- Tracer tests can effectively provide this critical information

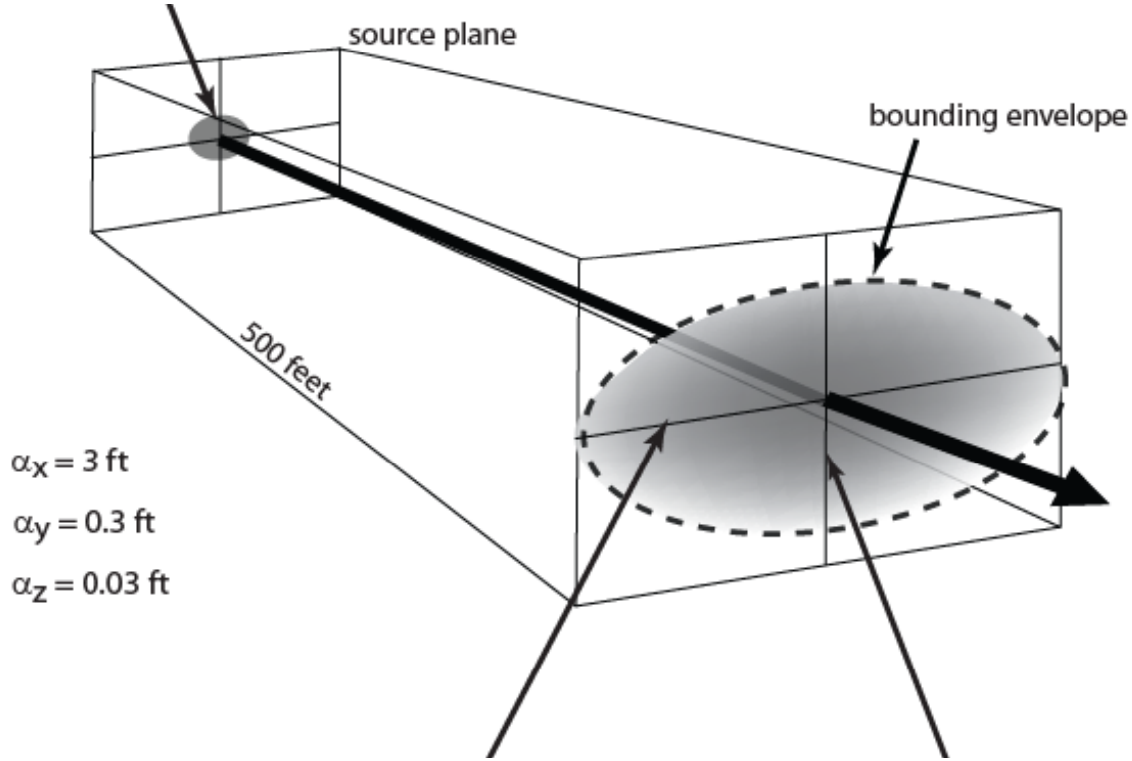
“We need to stamp out homogeneous isotropism from our thinking!”

Groundwater Always Takes The Path of Least Cumulative Resistance





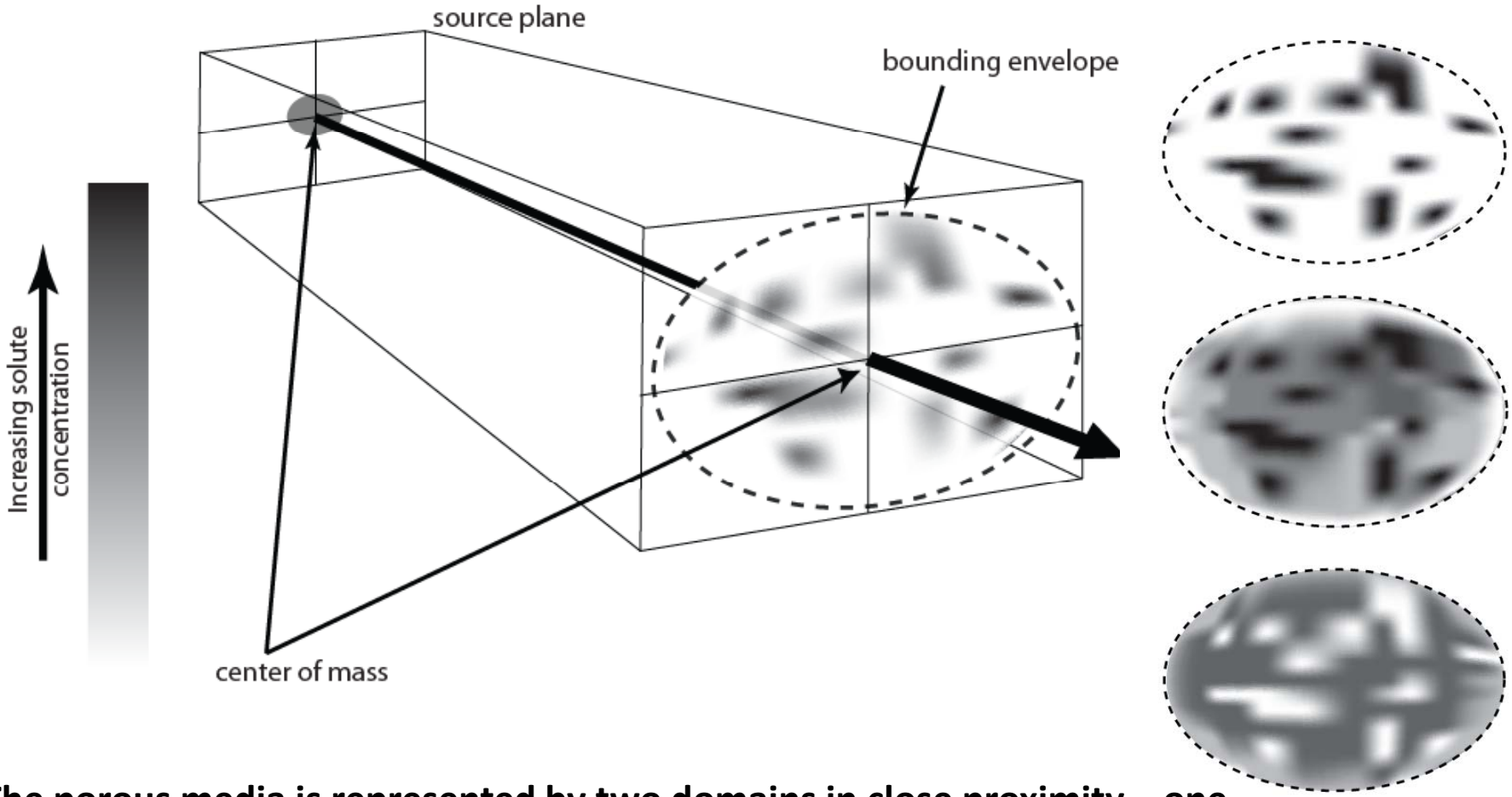
Classic Fate and Transport Model (i.e., the ADE)



However, what we observe…

- Peak transport velocity is much faster than average velocity
- Significant “tailing” is observed
- Transverse dispersive spreading is negligible
- Delivery and transport is highly variable between sites

A Better Conceptualization of Solute Transport



The porous media is represented by two domains in close proximity – one mobile, one immobile – and solute mass is exchanged via diffusion

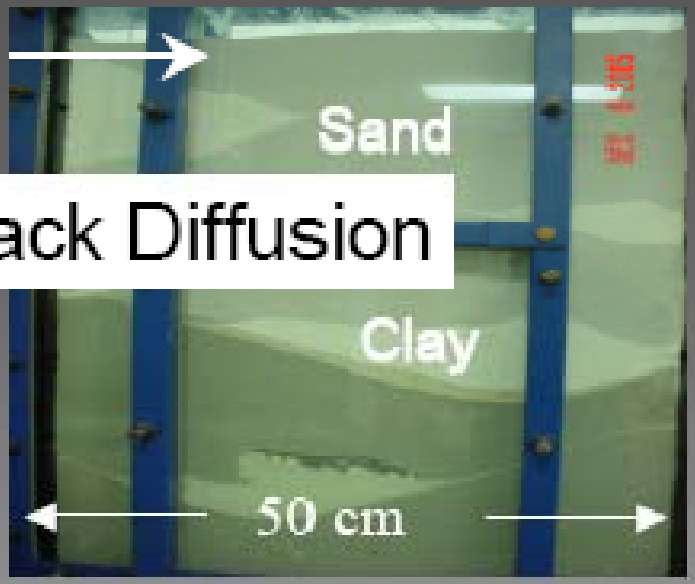


Figure 1.1: Setup - Sand and Clay

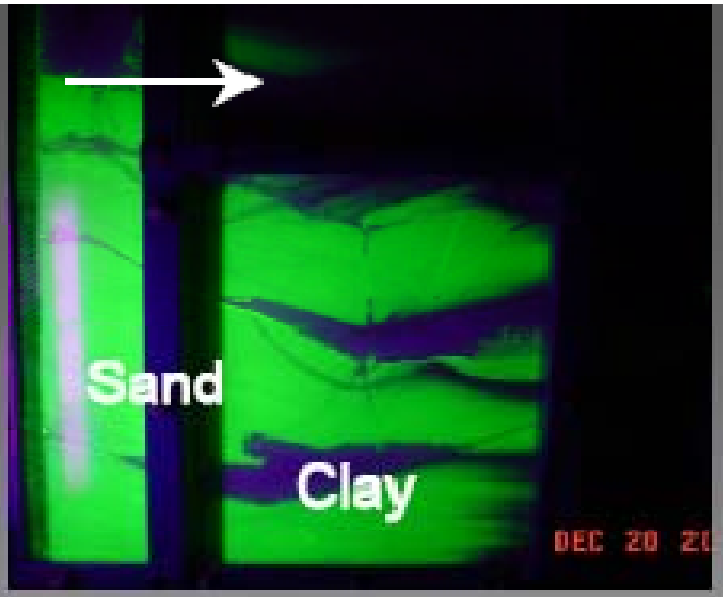


Figure 1.2: Fluorescein Inflow (Matrix Storage)

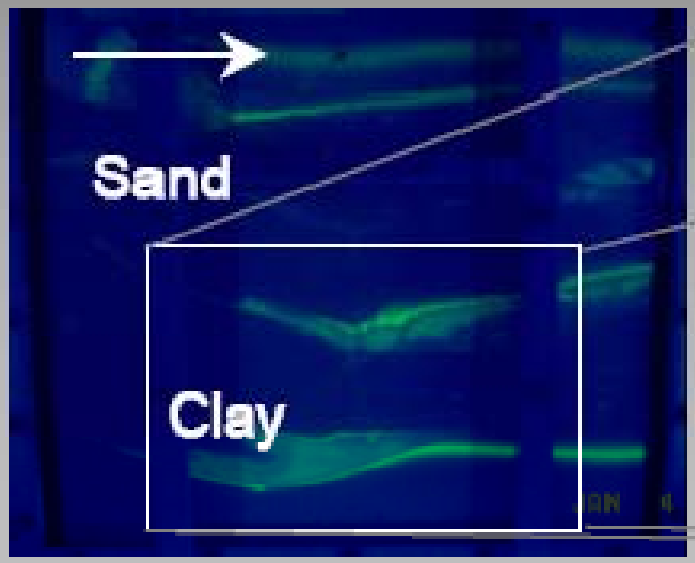


Figure 1.3: Source Off – Back Diffusion

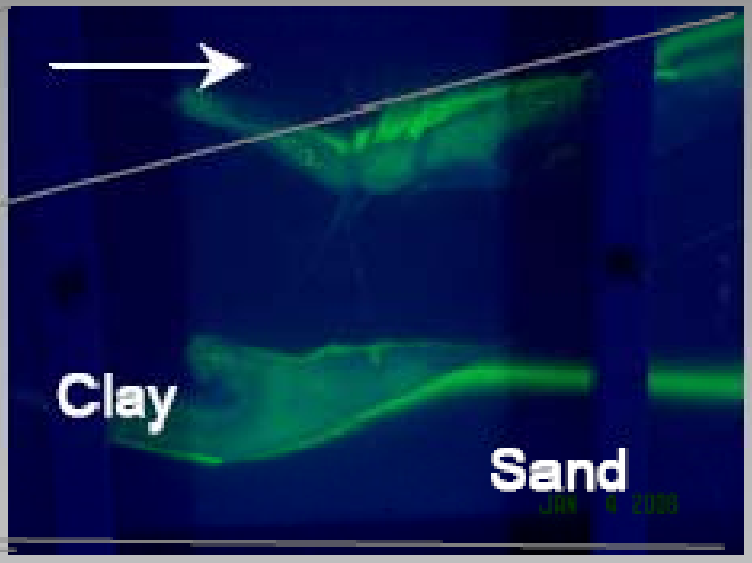


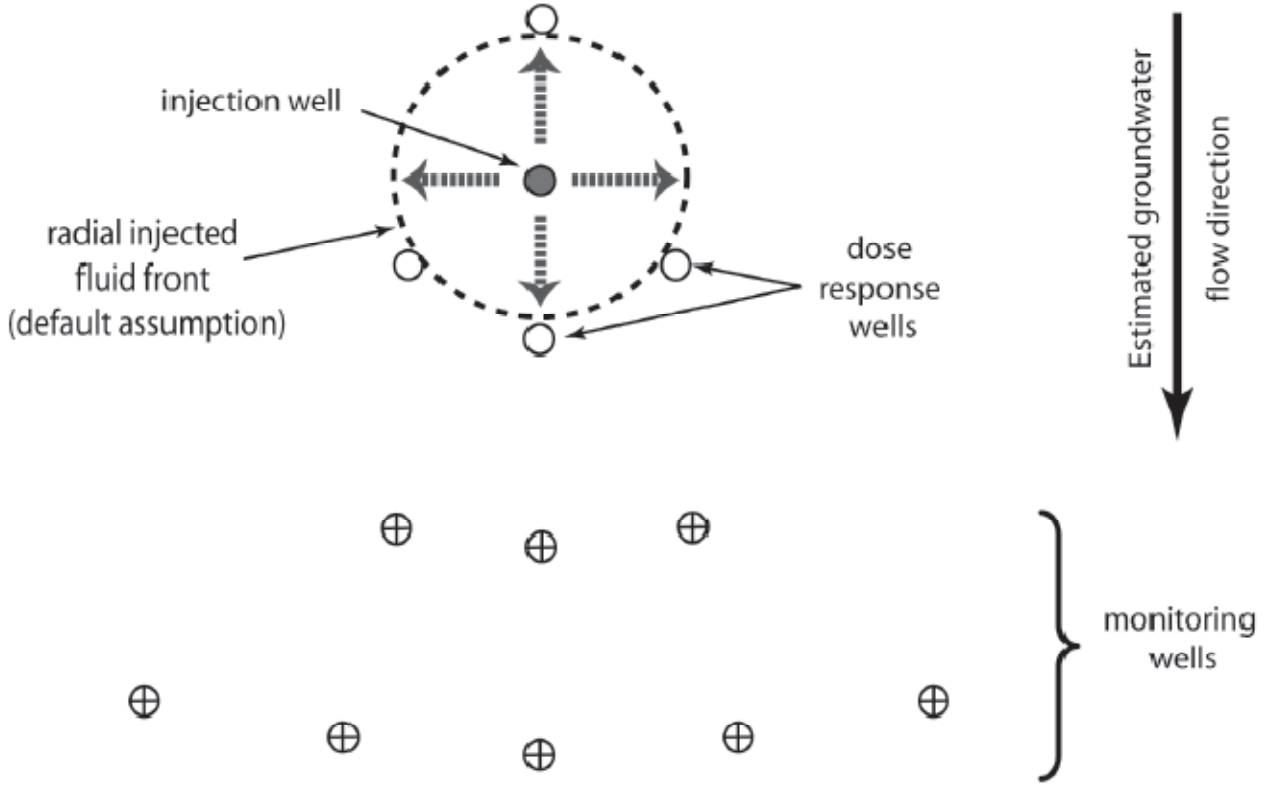
Figure 1.4: Close-up of Back Diffusion

How Does This Relate to In Situ Remediation?

- Coverage-volume relationship
  - What controls the lateral coverage we can accomplish from an injection well?
  - Does lateral (transverse) coverage increase downgradient from injection points?
- Reagent mass velocity
  - The peak and center of mass don't travel at the same rate
  - The center of mass travels slower than the groundwater velocity
- Reagent concentration
  - Dilution occurs as a result of diffusive migration into immobile pore space
  - Peak concentration occurs only in the most mobile pore spaces; concentrations in immobile pore spaces will be noticeably lower
  - The peak concentration decreases as a function of distance from the injection well

Success with in-situ technologies begins and ends with hydrogeology

Idealized Conceptual Well Network



Two phases

-injection (mobile porosity)

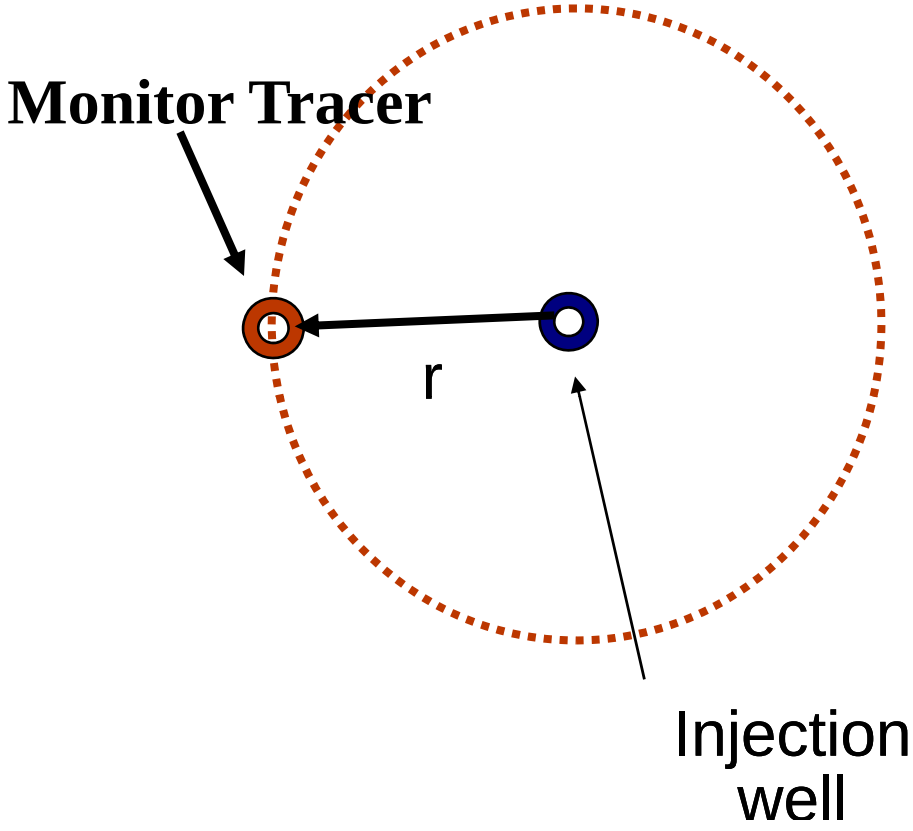
-drift (transport velocity, mass transfer)

Injection Phase – Calculating Mobile Porosity

- Inject whatever volume is needed to reach a planned radius

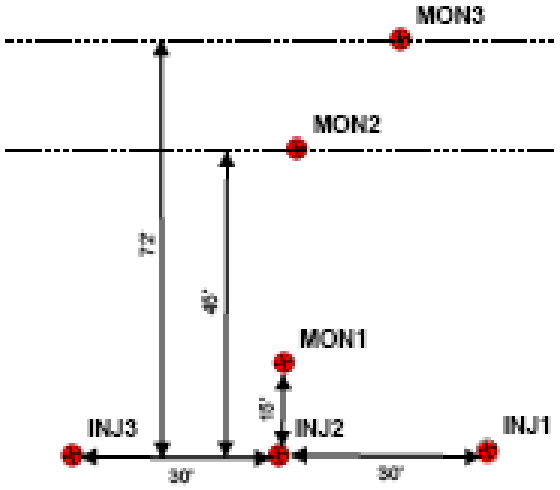
- Use a qualitative tracer to get real-time arrival
  - Conductivity (or "inverse conductivity)
  - Visual dye

- Use a quantitative tracer (typically fluorescent tracer) with low S/N ratio for porosity and transport characterization

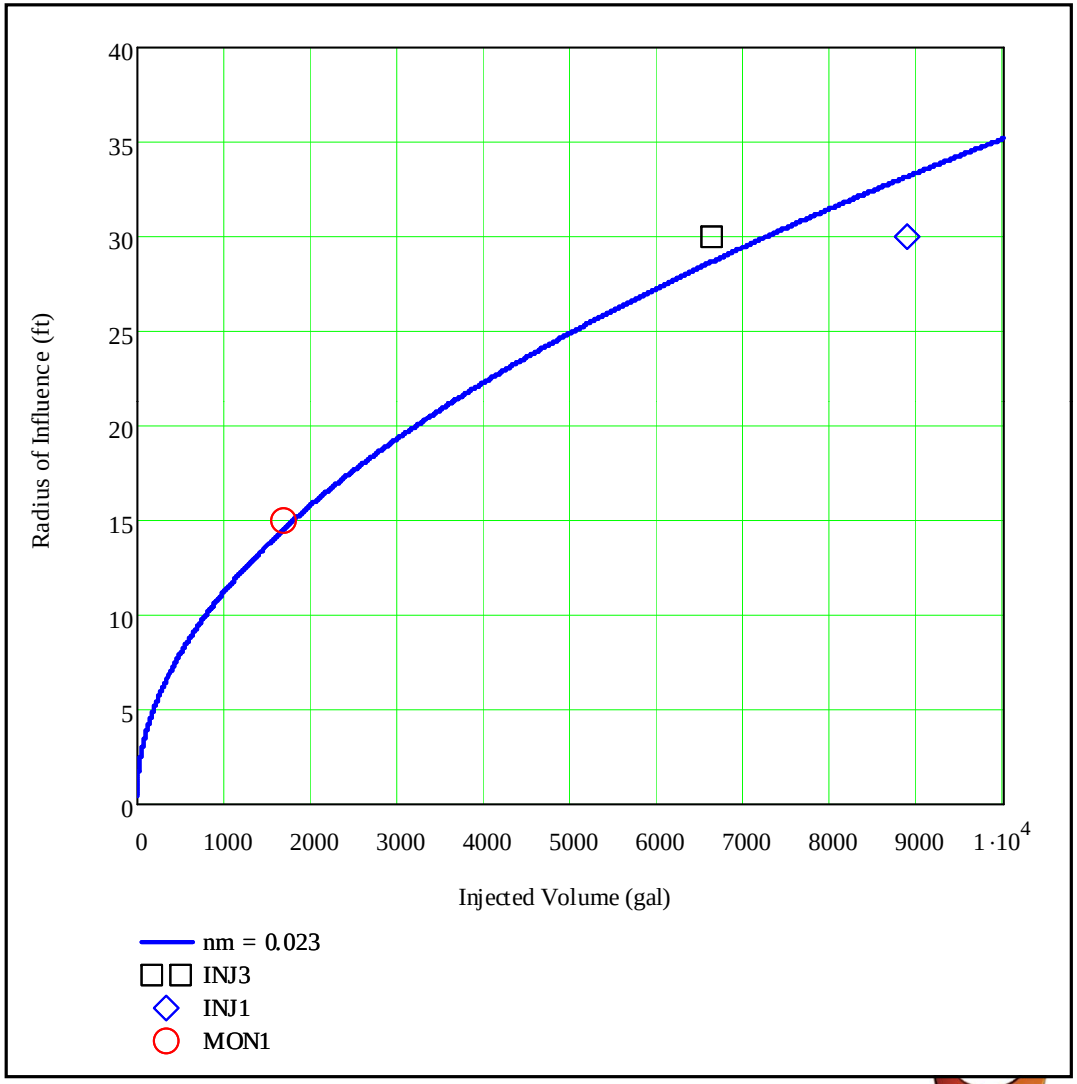


$$\theta_m = \frac{Injected\ volume}{\pi \cdot r^2 \cdot h}$$

Example: Calculating Mobile Porosity



$$\phi_m = \frac{V}{h \cdot r^2 \cdot \pi}$$



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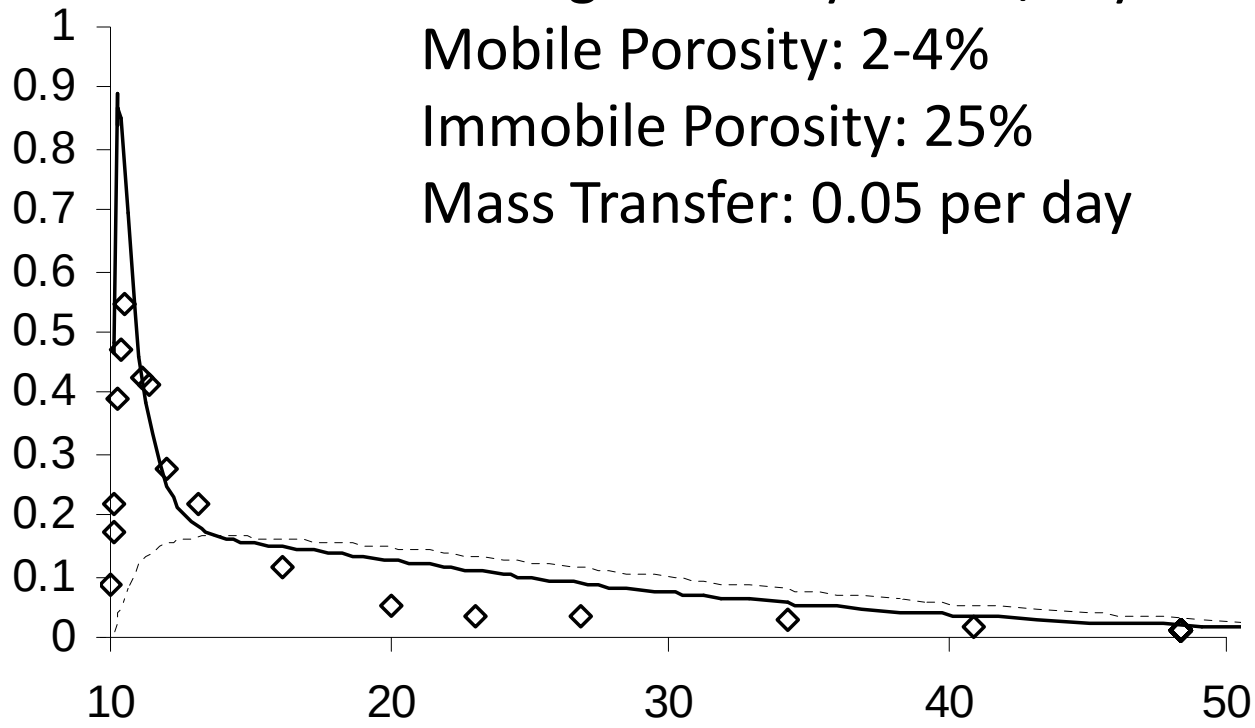
Example: Inverse Modeling of Drift Phase

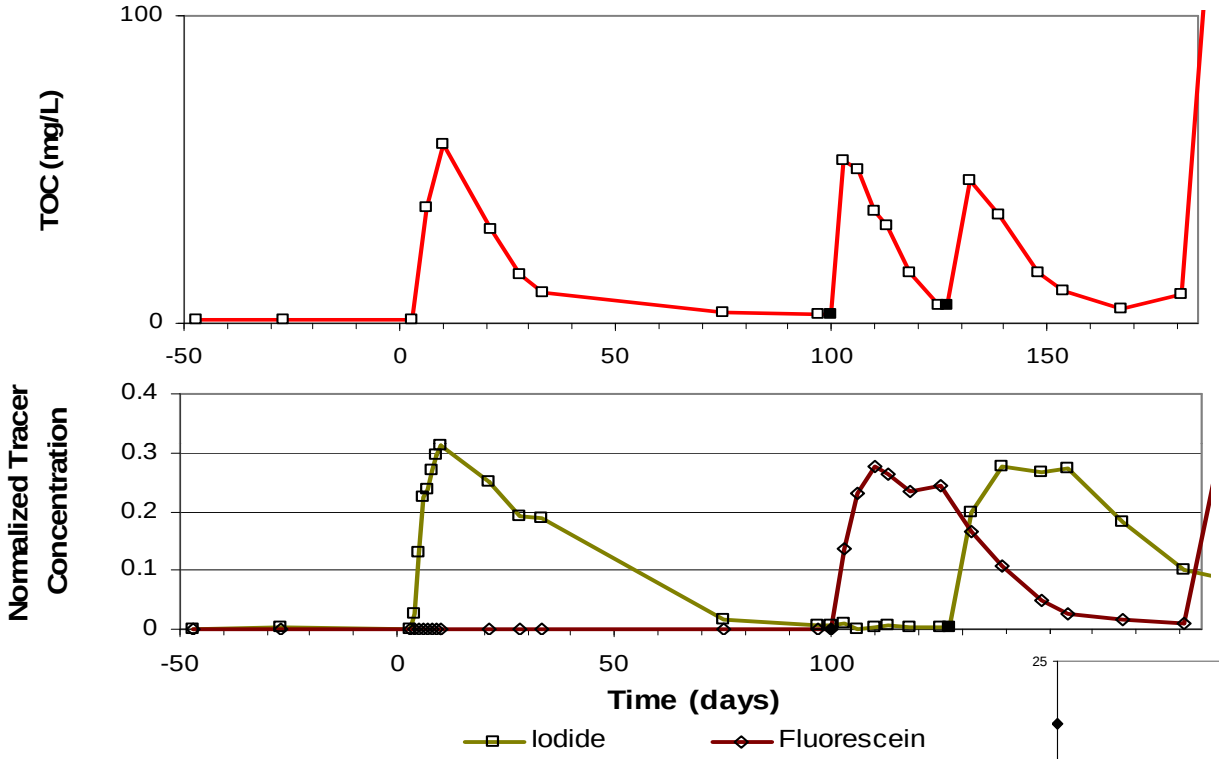
Peak Velocity: 5-10 ft/day
Average Velocity: 1-2 ft/day
Mobile Porosity: 2-4%
Immobile Porosity: 25%
Mass Transfer: 0.05 per day

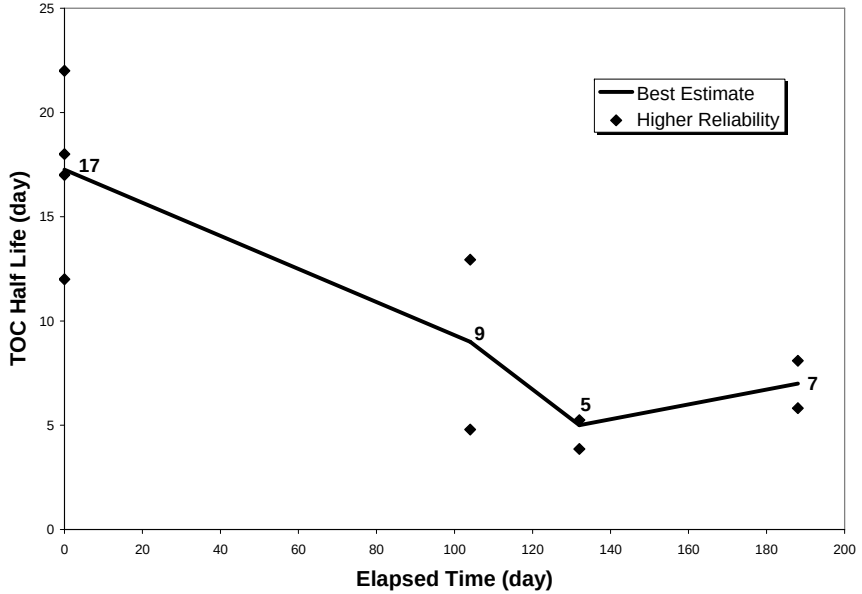


Key Information Relevant to Design

- High hydraulic conductivity
  - Aquifer has high injectability
- Low mobile porosity
  - Facilitates efficient amendment distribution
- Immobile porosity and mass-transfer
  - Diffusion-controlled tailing for conservative solutes will control period of performance
- May need to consider recirculation strategies for full-scale implementation

Quantifying Lactate Half-Life Over Time





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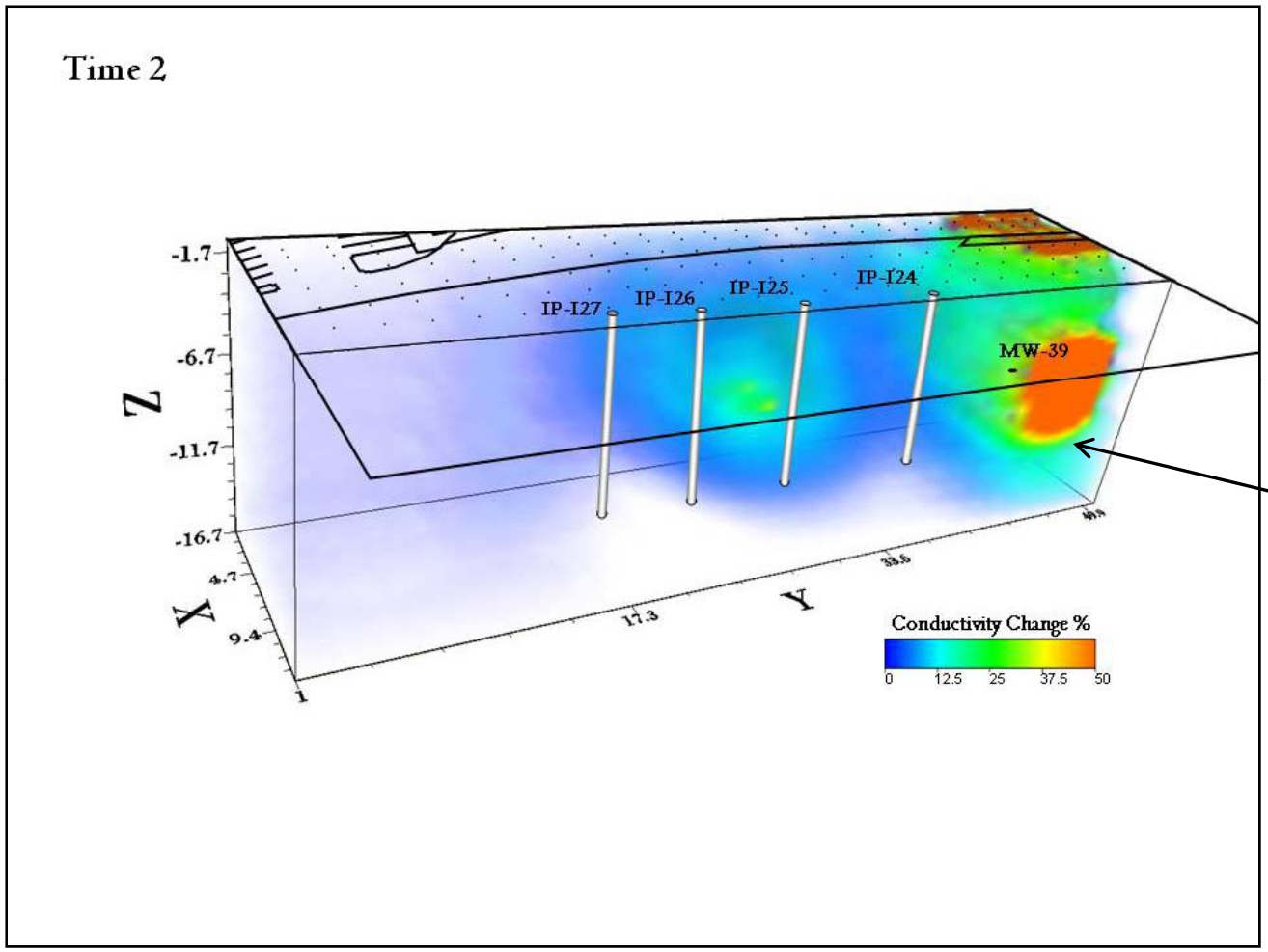
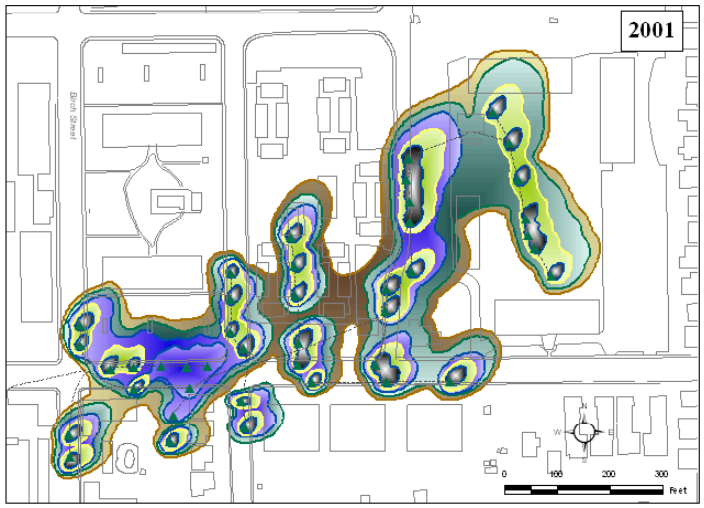
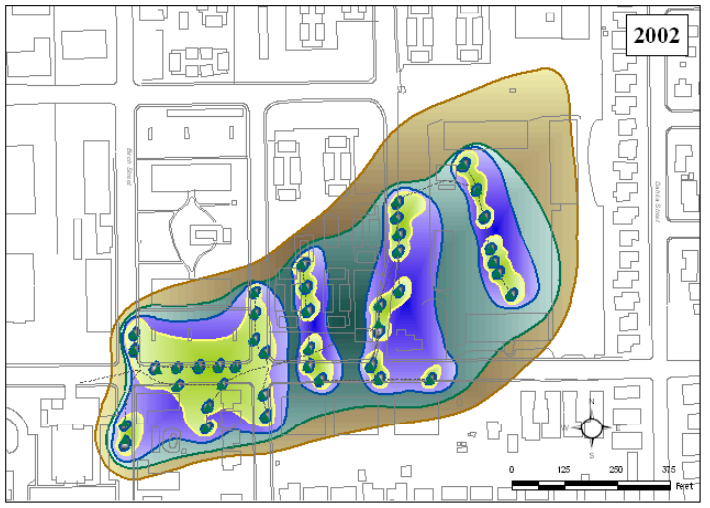
4D Mapping with Geophysics

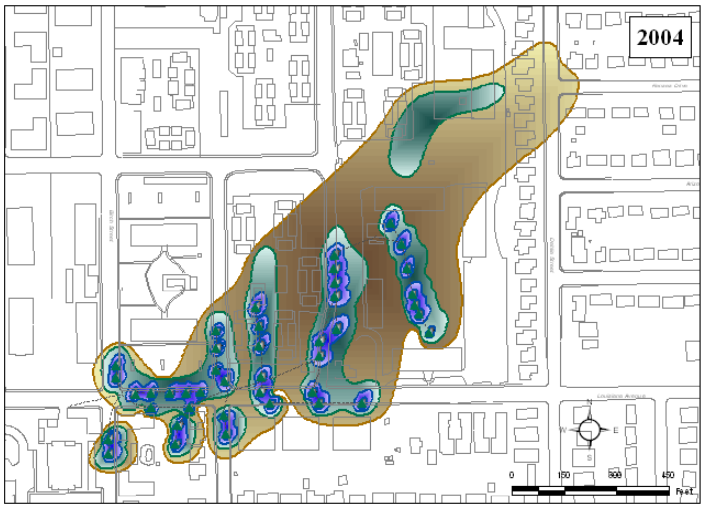


Amendment 5 hrs after injection

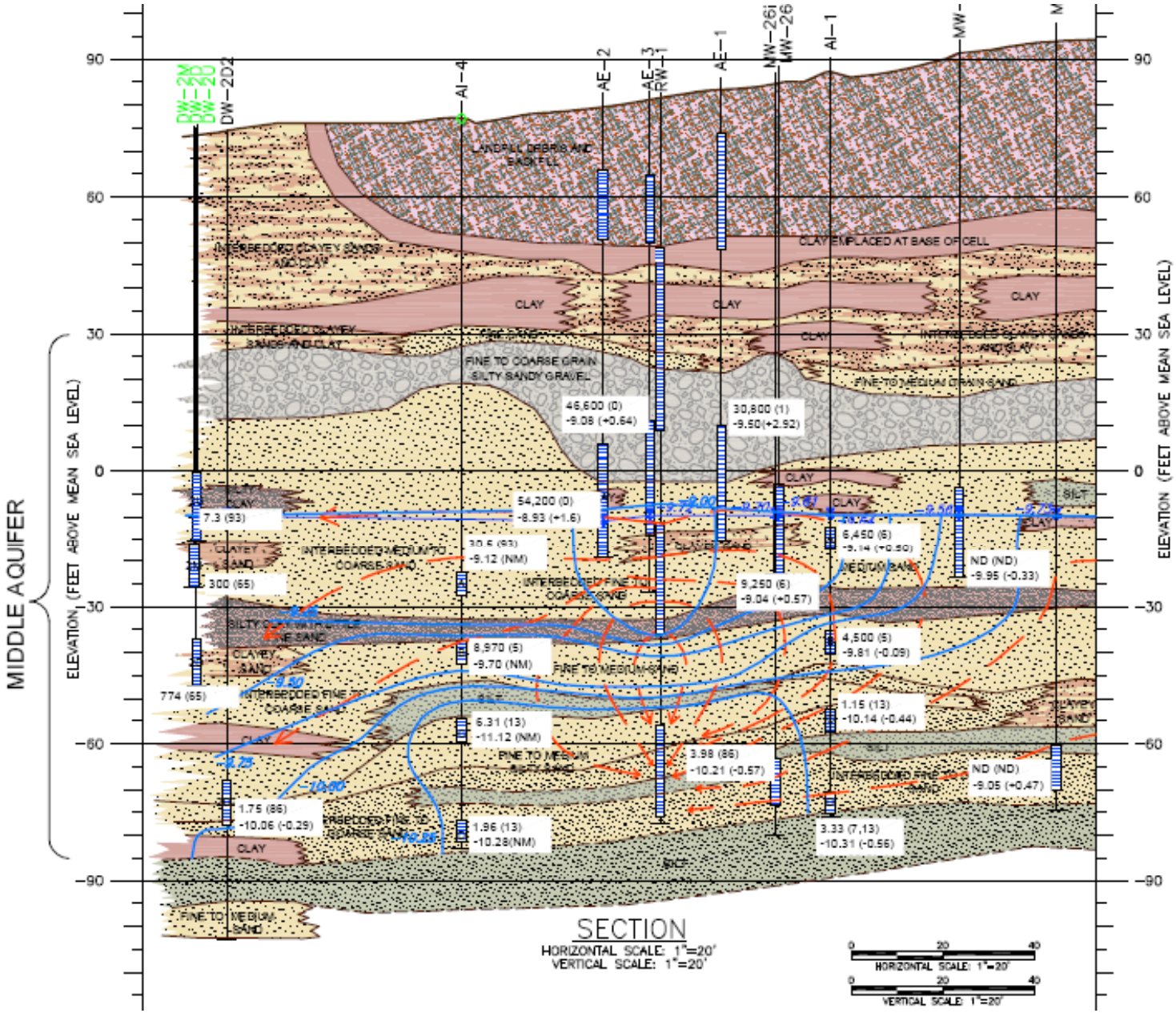
System Operation and Performance Assessment



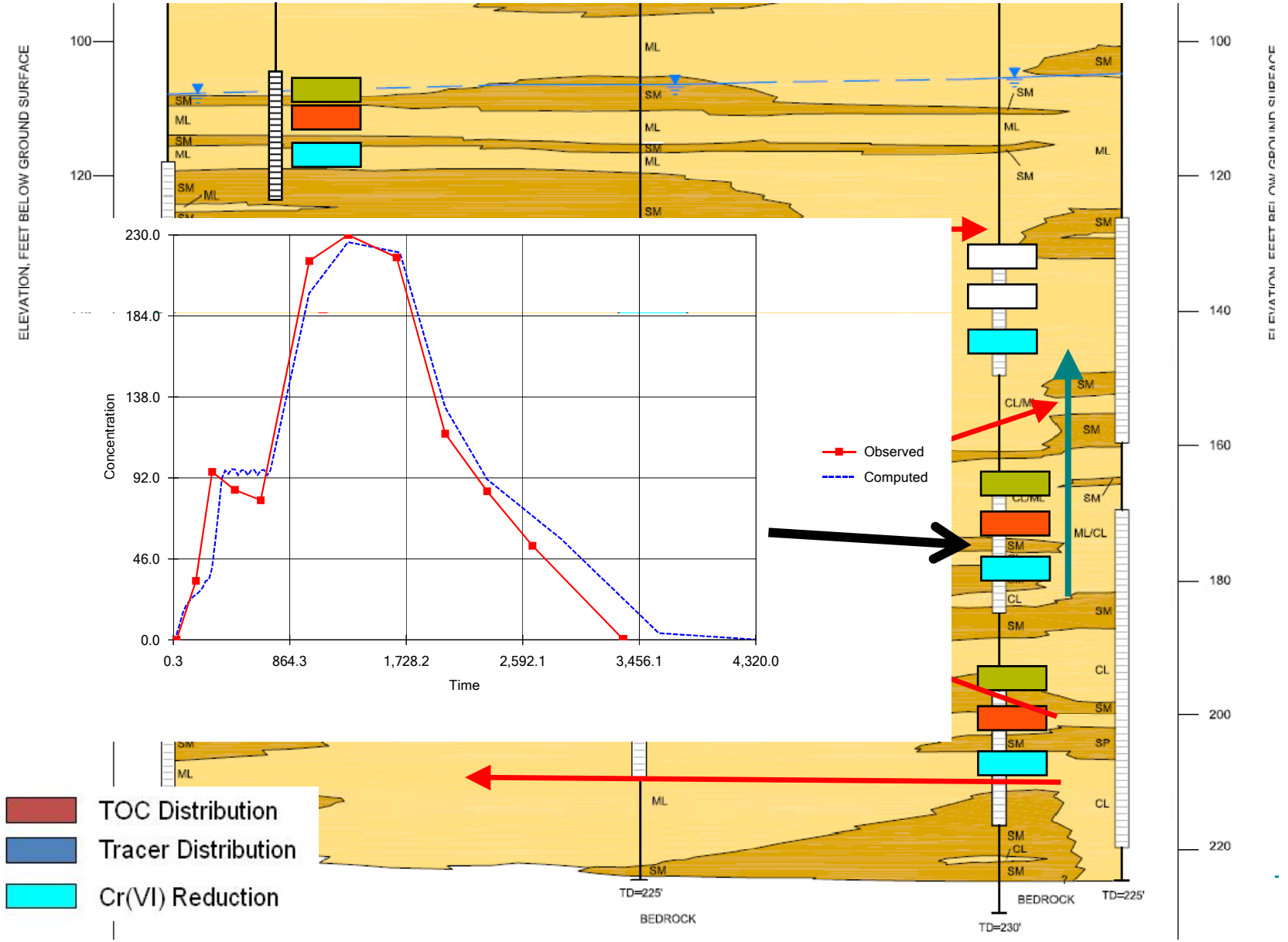




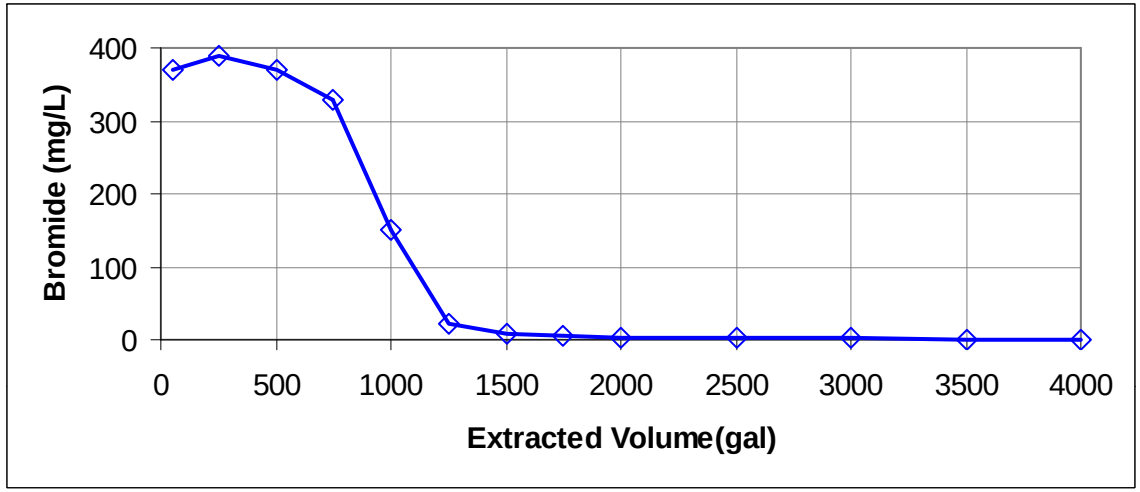
Recirculation System for Performance for Ammonia Treatment

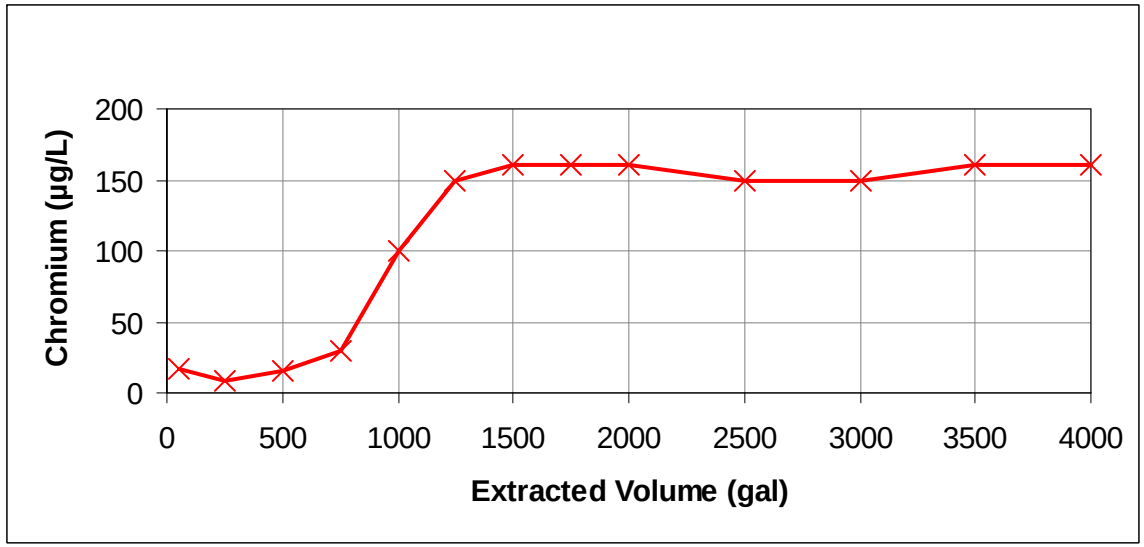


Ethanol Recirculation System for Cr (VI) Treatment



Push-Pull Test for Cr(VI) Sorption





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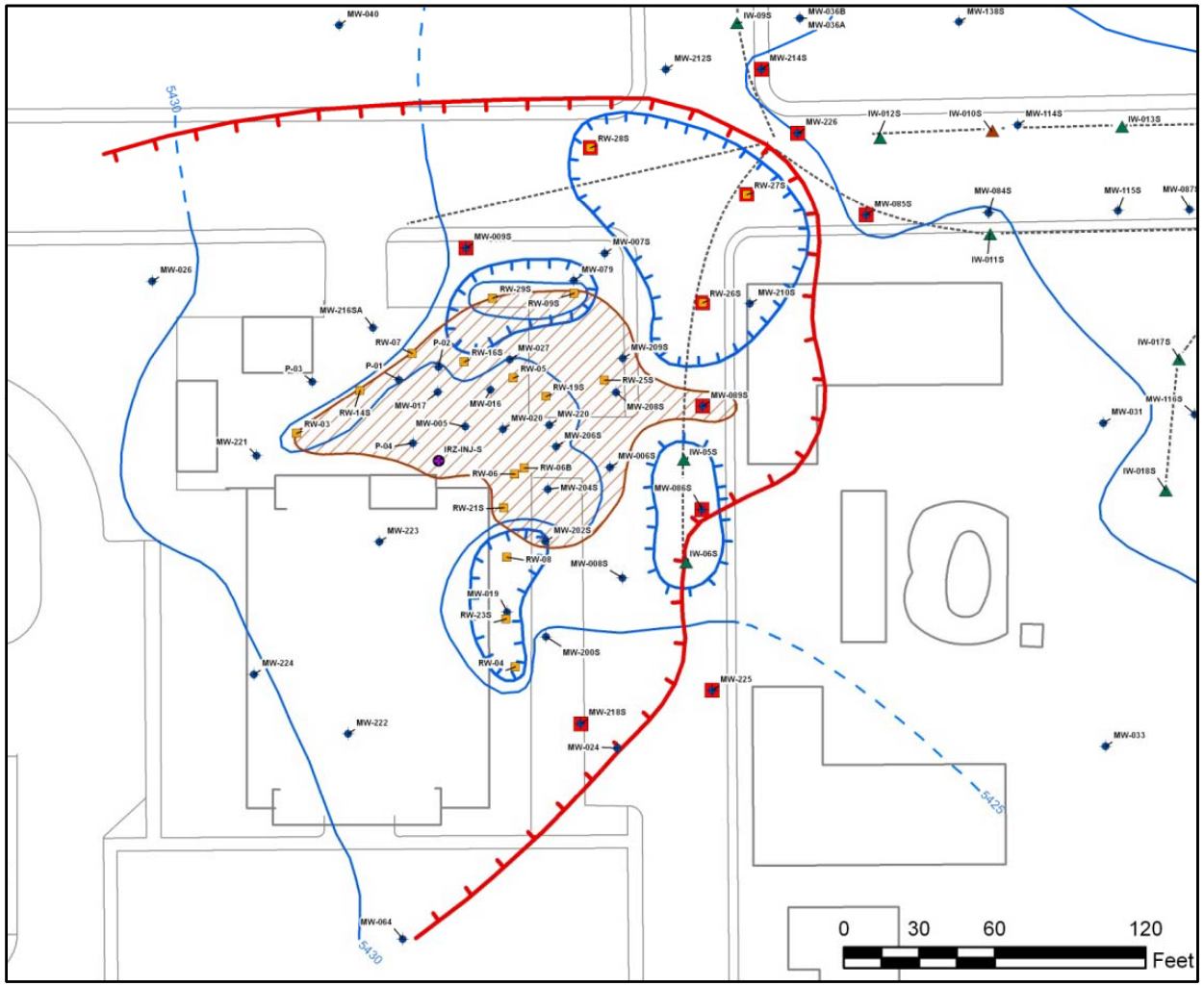
Capture Zone Confirmation



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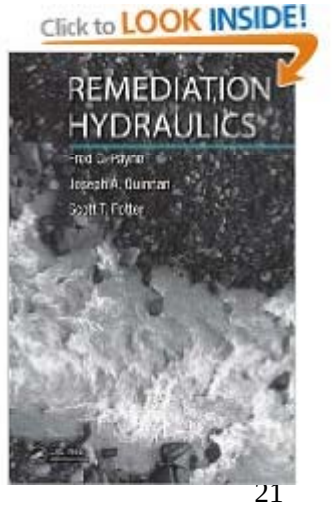
Future Directions

- Improved in-situ and “real-time” monitoring capabilities
- Development of practical test design tools
- Measure LNAPL mobility

Closing Thoughts

“There’s no truth like tracer truth.” James Quinlan

Tracers are the best tools for understanding how injected fluids and contaminants behave at the remediation (i.e., local) scale



Acknowledgements

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